Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

ORIGIN OF RESERVOIR FLUIDS OF THE GEOTHERMAL FIELD AT LOS AZUFRES, MEXICO

Peter Birkle[1], Broder Merkel[2] and Enrique Portugal M.[1]

[1] Instituto de Investigaciones Eléctricas, Unidad de Geotermia, A.P.1-475, Cuernavaca, Mor., 62001 México, E-mail: birkle@iie.org.mx
[2] Technical University of Freiberg, Institute of Geology, Gustav-Zeuner-Str. 12, 09596 Freiberg/Saxony, Germany

Key Words: fluid origin, residence time, isotopes, hydrological balance, recharge, Los Azufres field.

ABSTRACT

Hydrological balance calculations suggested a potential, average annual infiltration rate of 446 mm/m^2 for the Los Azufres area, which corresponds to a total of 82.2 million m^3 per year. Due to the highly fractured and faulted structure of the volcanic underground, a considerable potential for the infiltration of meteoric water into deeper sections of the volcanic formations can be assumed.

Isotopic data indicate the minor importance of recent meteoric water for the recharge of the geothermal reservoir. Very negative $\delta^{13}C$ values can be explained by the input of organic carbon from the surface, but the lack of ^{14}C in the deep fluids reflects a pre-historic age for the infiltration event. The dilution of the meteoric water by ^{14}C-free CO_2 gas from a shallow magma chamber complicates the exact age determination of the infiltration event, which probably occurred during Late Pleistocene or Early Holocene glacial periods.

Additionally, the positive δD and $\delta^{18}O$ trend of the geothermal brines towards an andesitic water composition indicates the influence of andesitic water, derived from the subduction of the Pacific Plate below the North American Plate.

Due to its heterogeneous isotopic composition, the geothermal reservoir in the southern reservoir zone can be divided into four vertical zones: a) a *rhyolitic sealing cap* without geothermal fluids, b) a *shallow infiltration zone* from 300 to 600 m, which is characterised by a temperature dependent oxygen isotopic exchange of the fluids, c) the m*ajor geothermal reservoir zone* from 800 to 1250m characterised by high water-rock interaction and, d) a *paleo-zone* at >1250m depth with restricted flow circulation, as indicated by constant δD-values.

A preliminary hydrological model of the reservoir is as follows: the fossil hydrodynamic system was characterised by the infiltration of meteoric water and mixing with andesitic and/or magmatic water. High water-rock interaction processes in the main part of the production zone indicate the existence of a former active fluid circulation system. Due to changes in pressure and temperature, the rising fluids get separated into a liquid and vapour phase at a depth of 1,500 m. After cooling, main portions of both phases remain within the convective reservoir cycle. Isotope analyses of hot spring waters indicate the connection of the reservoir with the surface at some local outcrops. A recent reactivation of the hydrostatic system is caused by geothermal production, as indicated by the detection of natural tracers in production wells.

1. INTRODUCTION

Since the beginning of the 1980´s, a mixture of geothermal liquid and vapour has been extracted from a depth between 350 and 2500 m at the Los Azufres geothermal field, located 220 km NW of Mexico City (Fig. 1). The origin of the fluids, the influence of surface recharge by meteoric water and/or regional aquifer systems, as well as the hydraulic conditions of the deep circulation systems are still unknown. The former questions will be of importance for the future potential of the geothermal production cycle. In the past, reservoir models were mainly based on thermodynamic parameters, such as P/T-conditions (Iglesias and Arellano, 1985) or phase distributions (Nieva *et al.*, 1983). Artificial tracer tests with KJ (Iglesias, 1983) and Iridium-192 (Aragón, 1985) were not able to detect any connection between individual wells, although reinjected brines caused elevated CO_2 and N_2 concentrations in adjacent production wells (Horne and Puente, 1989).

This paper tries to further understand the hydrodynamic processes of the Los Azufres geothermal reservoir, such as potential circulation systems, recharge processes and the origin of the fluids. Stable isotope analysis of surface outcrop and reservoir brines give indications about the existence of vertical geothermal fluid flow, as well as about the magnitude of water-rock interaction processes. The use of radioactive isotopes and the determination of their residence time reveal the existence of recent, or fossil, hydrodynamic processes within the reservoir. Hydrological balance calculations indicate the potential of recent infiltration of meteoric fluids into the shallow and deep aquifer system.

2. METHODS

Monthly and annual climatological data from 14 stations (one inside the field, 13 in the surroundings) from 1955 to 1979 (Cedillo et al, 1981) was used to calculate parameters of the hydrological balance for the study area, such as the average and total precipitation (*P)* and the potential evaporation rate (ET_{pot}) (Birkle, 1998). The actual evapotranspiration (ET_{actual}), which represents the sum of transpiration by plants and evaporated precipitation water, was determined by semi-empirical equations. The methods of Turc (Gray, 1973), Morton (Morton, 1965), Budyko (Kuzmin and Vershinin, 1974), and Coutagne (Remendieras, 1974) are based on climatological, atmospheric and vegetation data, such as the temperature, relative humidity, latent vapour heat, solar radiation, albedo effect and the potential evaporation.

During the dry season from October to May, the volume of surface discharge was derived by punctual hydrometric measurements with flowmeter equipment. Due to the lack of hydrometric stations in the study area, significant runoff fluctuations during the wet season were not measured directly in the field. Wet season discharge of the Los Azufres area was derived by the comparison of the dry/wet season discharge proportions from lower course, external stations. A methodical error of ±10%, ±25% and ±3% is considered for the determination of P, ET_{actual}, and the runoff measurements, respectively.

Stable isotope analysis (D, ^{18}O) of geothermal brines, and cold and hot springs were performed at the *Unidad de Geotermia* at the *Instituto de Investigaciones Eléctricas, Cuernavaca, Mexico* and the *Technical University of Freiberg/Saxony, Germany*. Four hundred L of geothermal brine with an HCO_3^- concentration of 143.3 mg/L were extracted from well Az-43. The carbonates were precipitated with $BaCl_2$ in the form of $BaCO_3$. CO_2 from 10 gas samples from wells Az-2, 4, 5, 6, 9, 22, 26, 28, 38, and 41 were concentrated in a vacuum vessel with a NaOH-saturated solution. Tritium, ^{13}C and ^{14}C-analysis on surface samples and geothermal brines were determined at the *Institute for Applied Physics* at the *Technical University of Freiberg/Saxony, Germany*. The residence times of the isotopes were calculated with MULTIS (Richter *et al.*, 1993).

3. RESULTS

3.1. Hydrological balance

The Los Azufres geothermal field is part of two hydrological basins, which is mainly due to its isolated, topographical high plateau position. A water shed divides the geothermal field in two lateral sections (Fig. 1). The northern part (Marítaro) discharges towards the Lago de Cuitzeo basin in NW-direction, whereas the southern part of the field (Tejamaniles) discharges towards the Río Balsas basin in SE-direction. The radial structure of the surface runoff confirms the unusual hydrological discharge conditions (Birkle, 1998).
Two case studies were developed to establish the hydrological characteristics of the geothermal reservoir:

a) Within the geothermal field area: Hydrological processes, which affect the deep reservoir, restricted to the lateral surface dimension of the geothermal field (total size: 30 km^2).
b) Surrounding the geothermal field area: The entire mountain plateau, including the surrounding lower foothill plains influences the geothermal reservoir by means of infiltration processes (total size: 183 km^2).

Results of the calculation of P, ET_{pot} and ET_{actual} are as follows. From March to May, high ET_{pot} rates and the lack of precipitation imply the complete absence of infiltration processes. The same is probably true for the winter months of December to February, where lower temperature conditions cause a decrease in ET_{pot}. Major infiltration processes can be expected during the rainy season from June to September, where P drastically exceeds the ET_{actual} rate.
The calculated quantitative hydrological balance resulted in a total annual input of 222.9 million m^3 of precipitation into a surface area of 183 km^2, which corresponds to 1330 mm/m^2 a year (Fig. 2). Evapotranspiration processes result in a loss of 47.9 % (637 mm), whereas 11.46 million m^3 (61.8 mm) and 34.38 million m^3 (185.7 mm) discharge is lost as surface runoff during the dry and wet season, respectively. A considerable amount of water (82.2 million m^3) is available for infiltration into the subsurface. Due to the highly fractured and faulted structure of the volcanic formations and the low abundance of shallow aquifers in the Los Azufres zone (Birkle *et al.*, 1997a), a large portion of meteoric water is considered to infiltrate into deeper sections of the bed rock.

3.2. Stable and radioactive isotopic composition

Influence of andesitic and magmatic water

Isotopic data from surface manifestations (cold and hot springs) and from production wells of the geothermal field of Los Azufres are illustrated in Figure 3. The composition of the deep fluids is shown as its total discharge during the initial (1980-1981) and intermediate (1985-87) period of geothermal production (Nieva *et al.*, 1983, Nieva *et al.*, 1987, respectively), as well as the recent composition of the geothermal liquids (1994-1996) (Birkle, 1998). The global meteoric water line, as well as the hypothetical composition of primary magmatic water from hydrous basalts and subduction-related andesitic water (Giggenbach, 1992) are shown.

The cold springs of the geothermal field are characterised by typical meteoric isotope compositions, although two samples (IV, V) with elevated δD and $\delta^{18}O$ values appear to be affected by evaporation processes. The total reservoir discharge from the initial years of the geothermal field (Nieva *et al.,* 1983) is characterised by the deviation of the $\delta^{18}O$ and δD-values from the global meteoric water line towards more positive values. According to Giggenbach (1992), very large ^{18}O shifts, such as those observed in Los Azufres, can not be explained exclusively by water-rock interaction processes. The positive isotopic trend of the initial fluid discharge, especially the increase in δD in comparison to recent meteoric water composition, indicates the influence of additional processes such as water-rock interaction processes for deep reservoir fluids. The Los Azufres fluids that plot between meteoric and andesitic water and/or magmatic water composition suggest a mixing between both components. If only a mixing process is considered, a mixture of about 70:30 between meteoric water and a magmatic component is most likely.

In general, mixing processes between two components are indicated by a positive tendency in the chloride and deuterium composition. Contrary to the expected positive trend, a heterogeneous distribution is observed for the Los Azufres brines. Thus, mixing of two components is not the dominating formation process of the reservoir fluids.

Vertical communication between the reservoir and hot springs

The hot springs and fumaroles from the geothermal field area range from a meteoric water composition to enriched δD and $\delta^{18}O$ values (Fig. 3). Four types of warm and hot springs can be distinguished:

a) A high mineralization type, enriched in typical geothermal tracer elements such as Cl, B and F as well as very positive δD (-43.9 to -24 ‰) and $\delta^{18}O$ (-3.8 to 5.6 ‰) values, indicate the direct rise of geothermal liquid and vapour to the surface. Examples are Marítaro and Laguna Verde.

b) Very low Tritium (0 T.U.), enriched δD (-24.1 ‰) and $\delta^{18}O$ values (5.4 ‰), low Cl and enriched SO_4-type. Reflecting shallow condensation of a rising vapour. The Currutaco spring is an example.
c) High Tritium values (up to 14.9 T.U.), H_2S-oxidation, intermediate δD (-57 to –62 ‰) and $\delta^{18}O$ (-4.5 to -5.8 ‰) values and low mineralization type. These are probably shallow aquifer waters (with a minimum residence time of 30 years) that have been heated up by ascending vapour. Examples are Gallo and Azufres (Birkle *et al*., 1997b).
d) Oxygen and hydrogen isotope values close to the meteoric water line and tritium concentrations similar to the recent atmosphere (1 - 4 T.U.). A meteoric water type, which has been slightly heated by rising vapour.

It can be concluded that some of the surface outcrops are in direct communication with fluids from the geothermal reservoir. Lower permeability of some reservoir zones and the occurrence of local shallow aquifer system favour the exclusive ascent of geothermal vapour, whereas the existence of vertical fault and fracture systems allows the direct rise of geothermal brine. The irregular lateral distribution of the individual hot spring types reflects the heterogeneous distribution of permeable formations and fault structures.

Vertical zonation – Water/rock interaction

In general, water-rock interaction processes are characterised by a positive shift of the $\delta^{18}O$ values of the liquid phase, while δD values remain stable. Figure 4 shows the vertical distribution of the initial $\delta^{18}O$ values from geothermal liquids (Giggenbach & Quijano, 1981; Nieva *et al*., 1983; Nieva *et al*., 1987) and from core samples (Torres-Alvarado, 1996) from different depths. The brine samples were derived from a specific production depth from several production wells, whereas the rock samples were extracted during the perforation of well Az-26. Due to the irregular field topography, the depth of the samples is given in m.a.s.l. Four trends were observed:

a) Rhyolites (2889 - 2569 m.a.s.l), forming the sealing cap of the andesitic geothermal reservoir, are characterised by homogeneous $\delta^{18}O$ values around 9‰, which represent the primary (non-altered) rock composition. Brine samples are not available from this shallow section.
b) Rocks under 2,600 m.a.s.l. show an abrupt shift in their $\delta^{18}O$ values, reaching values as high as +17‰. Below this depth the oxygen isotopic ratios decrease continuously in felsic whole rock samples, as well as in andesitic reservoir rocks. As the main production zone is located about 600 m below this level, the interaction with geothermal fluids is not yet significant and cannot explain this shift. Considering plagioclase the most important mineral phase in these rocks and assuming isotopic equilibrium with the geothermal fluids, the isotopic shift can be explained as the temperature effect during oxygen isotope exchange (Torres Alvarado, 1996). Water-rock interaction processes may increase the shift to lower $\delta^{18}O$ values, as shown in the volcanic rocks under ≈ 2,400 m.a.s.l.
c) From the upper part of the geothermal reservoir (2220 m.a.s.l.) towards the main production zone, the $\delta^{18}O$-brine values increase from –5.1 ‰ (well Az-17: 2300 m.a.s.l.) to – 2.0 ‰ (well Az-26: 1600 m.a.s.l.), whereas the solid values decrease from 9.0 to 4.7 ‰ in the interval from 2210 to 1750 m.a.s.l. This inverse relationship can be explained by increasing water-rock interaction processes with a maximum intensity at the main production zone. On the other hand, the linear isotopic trend from the surface meteoric water composition towards the lower part of the main production zone could indicate a decreasing influence of infiltrating meteoric water at the lower part of the geothermal reservoir.
d) Below the main production zone, the fluid composition is uniform, although a slightly negative trend can be observed. Even though no core samples were available, the constant trend in the fluid isotope composition suggests a minor effect of water-rock interaction, and hydrostatic conditions in the deeper part of the reservoir.

Residence time

In general, the detection of the radioactive isotope ^{14}C in deep aquifer systems proves its communication with the atmosphere during the last 40,000 to 200 years, whereas the abundance of tritium reflects infiltration processes since the bomb test period in the 60´s.

Measured tritium concentrations ranging between 0 and 0.4 T.U. ± 0.3 for the geothermal liquids and gases indicates an absence of infiltration of meteoric water into the reservoir during the last 30 years (Table 1). A more probable explanation is the complete natural decay of the radioactive isotope due to the long flow distance before reaching the reservoir at a depth from 600 to 2,500 m. The ^{14}C values of the geothermal liquids and vapour range between below the detection limit (6 samples) and maximum values of 1.7 ± 0.6 pMC for the gas sample of the well Az-41. High ^{14}C activities were observed in wells with a high abundance ratio between the vapour and liquid phase. Using an initial ^{14}C activity of 85 pMC for the infiltrating meteoric water, a minimum residence time of 32,000 years was derived for all reservoir samples. Assuming a theoretical mixing model with a “young water” (meteoric) and a magmatic water component for the Los Azufres geothermal reservoir, the contribution of the young water component is significantly less than 10 % (Birkle, 1998).

On the other hand, very negative $\delta^{13}C$ values up to –19 ‰ (well Az-43) can not be explained by the exclusive input of magmatic CO_2, which ranges between –5 and –8 ‰ (Taylor, 1986). Giggenbach *et al* (1983) define a general composition of –10 ‰ to -5 ‰ for $\delta^{13}C$ of geothermal and volcanic systems. Thus, the low values of the Los Azufres reservoir are due to the influence of surface water, which is enriched in atmospheric and organic CO_2 and depleted in ^{13}C.

3.3. Flow circulation model

Based on results of stable and radioactive isotope studies, a flow model of the geothermal circulation system with its individual components is proposed (Fig. 5). Meteoric water with a typical atmospheric stable and radioactive isotopic composition, such as negative ^{13}C values (-12 to -14‰) and enriched ^{14}C activity, infiltrated from the surface into the reservoir. Probably, the fossil recharge event was related to periods of increased humidity in Mexico, such as in Late

Pleistocene or Early Holocene. Portions of the geothermal fluids are derived from a deep lying magma chamber, which conducts heat and ^{14}C-free CO_2 gas with relatively negative δD values (-60 ‰) towards more shallow zones. Additionally, subduction related to a compressional tectonical regime from the Cretaceous to Recent period provided andesitic water to the regional aquifer system. Due to changes in pressure conditions, the single fluid phase was separated into a liquid and vapour phase at a depth of 1,500m. Both phases are characterised by differences in their isotopic composition. After cooling in the upper section of the reservoir, major parts of the phases remain within the convective geothermal cycle, whereas a minor part is rising directly towards a shallow aquifer system and towards the surface.

4. DISCUSSION

The positive δ^{18}O and δD trend of the Los Azufres brines towards an andesitic water composition seems to indicate mixing processes between a meteoric and a magmatic/ andesitic component in the geothermal reservoir. The andesitic component is probably related to the subduction of oceanic crust below the North American Plate from the Cretaceous to the Recent period. The influence of an atmospheric component is reflected by the abundance of very negative ^{13}C-values (-19 ‰), indicating an organic input into the reservoir by meteoric water. The combination of negative ^{13}C values and the lack of ^{14}C at the geothermal reservoir indicates the infiltration of meteoric water during pre-historic times, probably as part of the Late Pleistocene and/or Early Holocene glacial periods as well as dilution of paleo-meteoric water by ascending magmatic CO_2 without any radioactive carbon. The latter effect makes it difficult to determine the exact timing of the infiltration event.

The former existence of a hydrodynamic flow system and active circulation paths is reflected by strong water-rock interaction within the main production zone. Recently, the fossil hydrodynamic system has been reactivated by geothermal production, which is indicated by the occurrence of reinjected tracers in production wells. Although the upper and lower part of the reservoir has low permeability, flow to the surface seems to take place by cooling fractures and fault systems (Suárez et al, 1995).

5. CONCLUSIONS

Highly fractured volcanic rock units in the Los Azufres area permit fast and deep infiltration of recent meteoric water into the deeper aquifer systems. Hydrological balance calculations support the presence of a considerable amount of meteoric water available for recharge processes. Subtracting the fraction of meteoric water lost by evapotranspiration and discharging surface, the amount of 446 mm/m^2 a year (total annually: 82.2 million m^3) is nowadays available for recharging deeper aquifers.

On the other hand, radioactive isotopes indicate that natural recharge of the reservoir occurred during pre-historic time, probably during Holocene and/or Pleistocene glacial periods. As a second component, the trend of δD and δ^{18}O values towards an andesitic water composition could reflect the influence of magmatic fluids as a consequence of subduction of oceanic crust below the North American Plate.

The high water-rock interaction, especially in the main production zone of the reservoir, reflects the former existence of a fossil, hydrodynamic system with active fluid circulation. The recent reactivation of the hydrodynamic system by geothermal production is indicated by the detection of reinjected tracers in production wells.

ACKNOWLEDGEMENTS

The authors are greatful to Prof. Dr. D. Hebert and Dr. O. Nitzsche, *Institute for Applied Physics* at the *Technical University of Freiberg/Saxony, Germany*, for the Tritium, ^{13}C, and ^{14}C analyses, as well as to one anonymous reviewer for his helpful comments.

REFERENCES

Aragón, A.A. (1985). *Uso de trazadores radioactivos en la zona norte del campo geotérmico de Los Azufres.* CFE, Depto. Yacimientos, Internal Report 1385-004.

Birkle, P. (1998). *Herkunft und Umweltauswirkungen der Geothermalwässer von Los Azufres, Mexiko*. Wissenschaftliche Mitteilungen, Technical University of Freiberg, Freiberg/Saxony, Germany, Vol. 6, 226 pp.

Birkle, P., Torres R.V., and González, P.E. (1997a). El papel del sustrato geológico en el escurrimiento superficial y en los acuíferos del campo geotérmico de Los Azufres. *Ingeniería Hidraúlica en México*, Vol. XII (2), p. 37-48.

Birkle, P., Torres R.V., and González, P.E. (1997b). *Estudios hidroquímicos e isotópicos sobre el origen de las fumarolas y manantiales calientes de Los Azufres, Michoacán*. Proceedings, 5to. Congreso, Asociación Geotérmica Mexicana, Guanajuato, Gto., Mexico, pp. 91-96.

Cedillo, F.R., Silva, R.P., and Vargas, H.L. (1981). *Estudio geohidrológico del área de Los Azufres-Cuitzeo, Estado de Michoacán*. CFE, Subgerencia de Estudios Geotérmicos, Internal report 37/81, 4 volumes.

Contreras, E., Iglesias E., and Oliver, R. (1984). *Determinación de propriedades físicas y estudos petrográficos de nucleos de perforación del campo geotérmico Los Azufres*. IIE, Cuernavaca, Internal report IIE/11/3753/I 01/F, 90 pp.

Giggenbach,, W. (1992). Isotopic shifts in water from geothermal and volcanic systems along convergent plate boundaries and their origin. *Earth Planet. Sci. Lett*., 113, pp. 495-510.

Giggenbach W., Gonfiantini R., and Panichi, C. (1983). Geothermal systems. In: *Guidebook on Nuclear Techniques in Hydrology*, International Atomic Energy Agency, Technical Reports Series, no. 91, pp. 359-380.

Giggenbach, W. and Quijano, J.L. (1981). *Estudio isotópico de las aguas del campo geotérmico de Los Azufres*. Comisión Federal de Electricidad, Mexico, Internal report.

Gray D.M. (1973). *Handbook of Principles in Hydrogeology.* Water Information Center Inc., Huntington, N.Y.

Horne, R.N. and Puente, H. (1989). *Tracer testing at Los Azufres.* Proceedings, 14th Workshop on Geothermal Reservoir Engineering, Stanford, California, pp. 197-199.

Iglesias, E.R. (1983*). Reporte de avance del primer intento de utilización de trazadores en el campo geotérmico de Los Azufres.* Memorias de la Primera Reunión Interdisciplinaria CFE-IIE, Los Azufres, Michoacán, México, pp. 161-170.

Iglesias, E.R. and Arellano, V.M. (1985). *Apoyo en ingeniería de yacimientos para el campo geotérmico de Los Azufres. Fase 1: Integración de un modelo básico del yacimiento*. Instituto de Investigaciones Eléctricas, Cuernavaca, Internal report IIE/11/1864/I 04/F.

Kuzmin P.P. and Vershinin A.P. (1974) *Determination of evaporation in case of absence or inadequacy of data.* Proc. of the Madrid Symposium. Studies and reports in hydrology. UNESCO-WMO-IASH, Vol. 16, pp. 217-226.

Morton F.I. (1965) *Potential evaporation and river basin evaporation.* Proceedings of the ASCE, Journal of the Hydraulics Division, Vol. 91, pp. 67-97.

Nieva, D., Quijano, J., Garfias, A., Barragán, R.M., and Laredo, F. (1983). Heterogeneity of the liquid phase, and vapor separation in Los Azufres (Mexico) geothermal reservoir. 9th Workshop on Geothermal Reservoir Engineering, Stanford, California, pp. 253-260.

Nieva, D., Barragán, R.M., Cathalineau, M., González, E., Oliver, R., Portugal, E., Santoyo, E., and Verma, M. (1987). *Estudio de la estructura hidrológica y de la distribución de parámetros fisico-químicos en el yacimiento de Los Azufres, Mich., Fase II.* IIE, Internal report IIE/11/2011/1, 159 pp.

Remendieras G. (1974). *Tratado de Hidrología Aplicada.* Barcelona, España.

Richter, J., Szymczak, P., Abraham, T., and Jordan, H. (1993) Use of combinations of lumped parameter models to interpret groundwater isotopic models. *J.Contam. Hydrol.,* Vol. 14, pp. 1-13.

Suárez, M.C., Ortega, L.P., and Luis del Río (1995) *Fifteen years of development of Los Azufres geothermal field, Mexico*. World Geothermal Congress Proceeedings, Florence, Italy, Vol. 3, pp. 1791-1796.

Suárez, M.C. (1991). Capacidad energética del sector Tejamaniles. Geotermia, Rev. Mex. Geoenergía, Vol. 7, pp. 391-324.

Taylor, B. (1986). Magmatic volatiles: Isotopic variation of C, H, O, and S. In: *Stable isotopes in high temperature geological processes. Reviews in Mineralogy*, W.J. Valley, P.H. Taylor, and R.J. O´Neil (Eds.), Vol. 16, 185 pp.

Torres-Alvarado, I.S. (1996). *Wasser/Gesteins-Wechsel-wirkung im geothermischen Feld von Los Azufres, Mexiko.* Mineralogische, thermochemische und isotopengeochemische Untersuchungen, Tuebinger Geowissenschaftliche Arbeiten, Reihe E, No. 2, 181 pp.

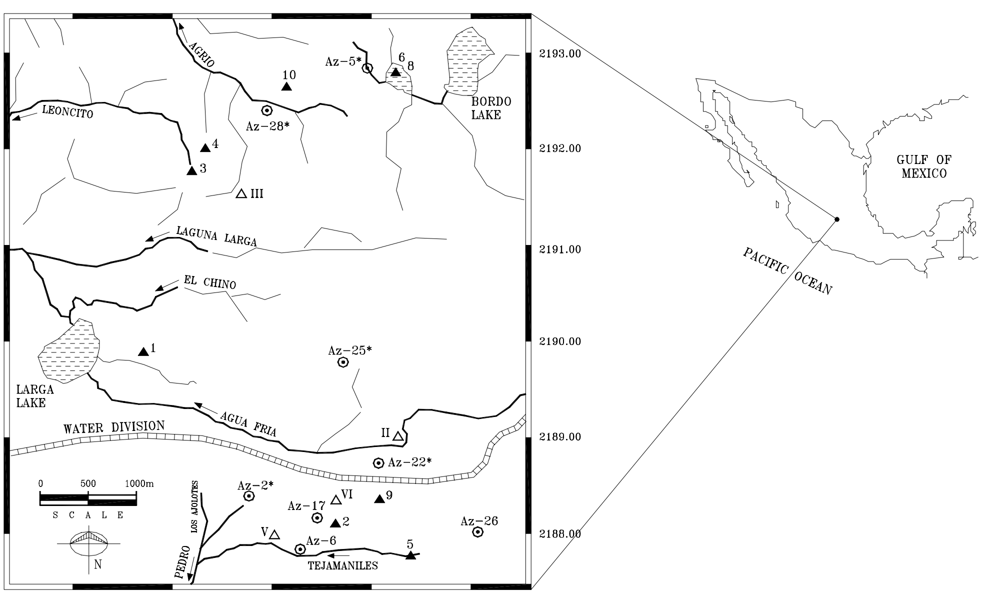

Figure 1. Location of the Los Azufres geothermal field with the sampled cold (I Ciudad Hidalgo, II Campamento, III-IV adjacent to the wells Az-47, 17, 6) and hot springs sites (1 San Alejo, 2 spring of brook Leoncito, 3 adjacent to Az-17, 4 Gallo, 5 Azufres, 6 + 8 Laguna Verde, 7 spring of river Agrio, 9 Currutaco, 10 Marítaro), geothermal wells (with *) and reference wells, as well as the water division between the northern and southern part of the field.

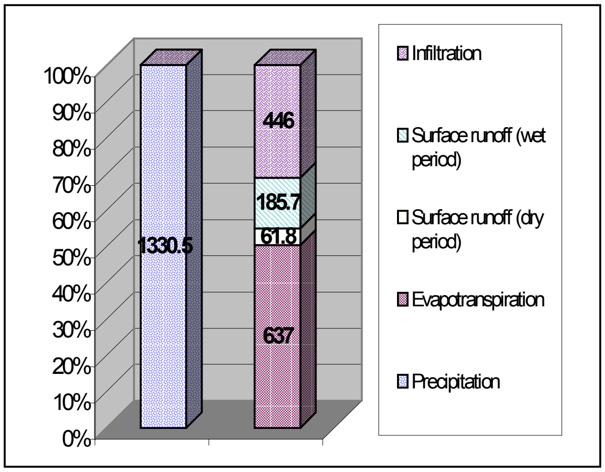

Figure 2. Quantitative distribution of precipitation (*P*), potential evaporation (ET_{pot}), actual evapotranspiration (ET_{actual}) of the Los Azufres geothermal area.

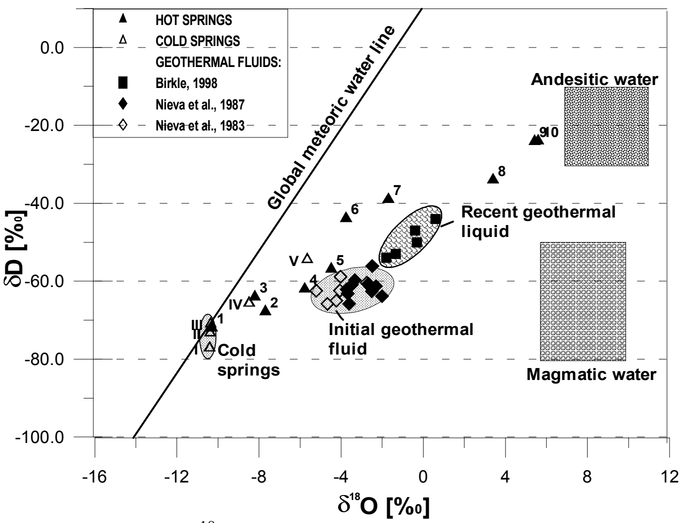

Figure 3. $\delta^{18}O$ vs. δD of geothermal brines, cold and hot springs of the Los Azufres geothermal field (Loc. in Fig. 1) in comparison with andesitic and magmatic water.

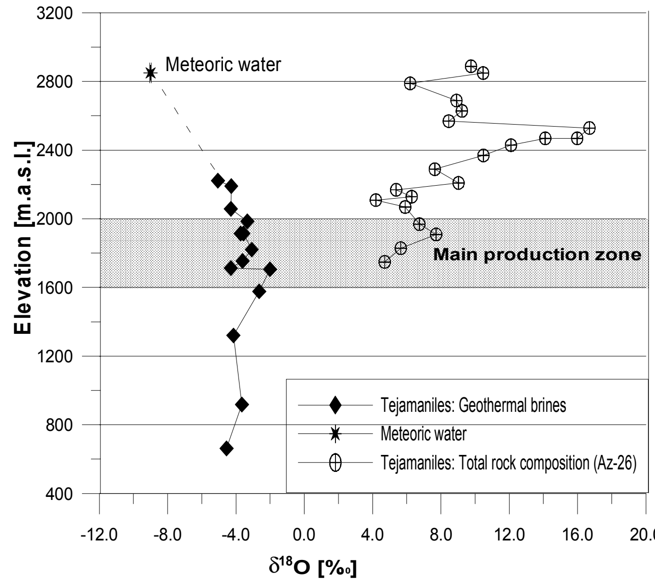

Figure 4. Vertical distribution of the $\delta^{18}O$ and δD values of geothermal brines, compared with the isotopic composition of the core from the Az-26 well.

Table 1. Results of tritium, ^{13}C and ^{14}C-analyses, and the calculated residence time (n.d. not detected; - not measured).

Well	T.U.	$\delta^{13}C$ [‰]	^{14}C-activity [pMC]	Residence time (y)
Az-4	-	-12.7	n.d.	n.d.
Az-5	0.0 ± 0.3	-5.4	≤ 1.4	≥ 34,000
Az-9	-	-8.4	n.d.	n.d.
Az-28	0.1 ± 0.3	-11.1	n.d.	n.d.
Az-41	-	-8.2	1.7 ± 0.6	32,000
Az-43	-	-19.5	n.d.	n.d.
Az-2	0.0 ± 0.3	-12.6	n.d.	n.d.
Az-6	0.4 ± 0.3	-11.4	≤ 0.9	≥ 37,000
Az-22	0.0 ± 0.3	-6.9	n.d.	n.d.
Az-26	-	-14.5	< 1.0	≥ 37,000
Az-38	-	-16.1	< 1.0	≥ 37,000

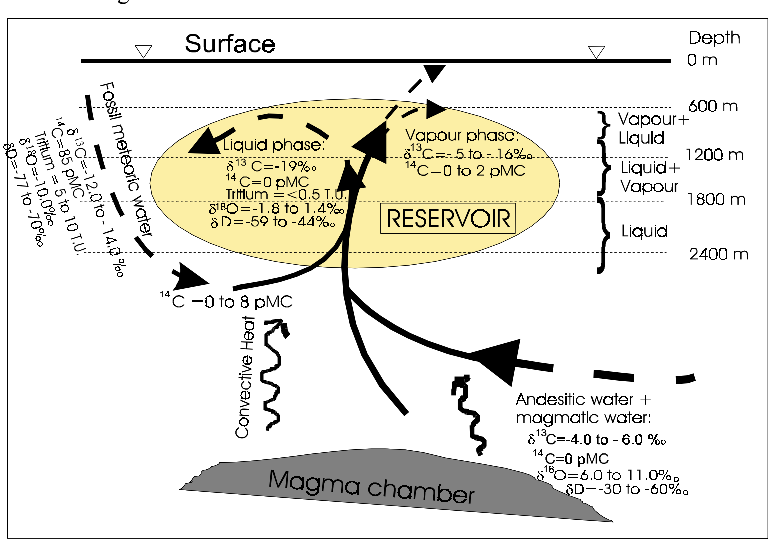

Figure 5. Flow circulation model of the Los Azufres geothermal reservoir, based on isotopic data.